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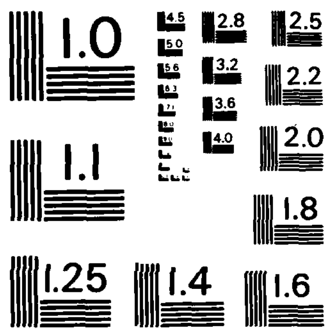

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ABSTRACT

The nonlinear optical properties of $Hg_{1-x}Cd_xTe$ for x values between 0.20 and 0.23 have been evaluated experimentally under CO_2 laser excitation at 295°K, 77°K, and 12°K. Optical phase conjugation arising from conduction band nonparabolicity and the photoexcited plasma mechanisms has been studied. Third order susceptibility values ranging from 1×10^{-8} esu (conduction band nonparabolicity) to 3×10^{-2}esu (photoexcited plasma) have been measured. A new effect in which the phase conjugate signal is erased or quenched by means of a separate CO_2 laser has been observed. The mechanism depends upon an enhanced Auger recombination rate due to two-photon absorption. Optical absorption data were obtained on eight samples of $Hg_{1-x}Cd_xTe$ over the interval from 10μm to 40μm and interpreted theoretically in terms of interband, intraband, impurity, and lattice absorption measurements. The temporal behavior of degenerate four-wave mixing and optical bistability was studied theoretically for a superlattice or quantum well for both absorptive (photoexcited plasma) and dispersive (conduction band nonparabolicity) mechanisms. The third order susceptibility due to both conduction band nonparabolicity and the photoexcited plasma mechanisms in both $GaAs/Al_xGa_{1-x}As$ and $Hg_{1-x}Cd_xTe/Hg_{1-y}Cd_yTe$ superlattices has been investigated theoretically. The optimized $GaAs/Al_{1-x}Ga_xAs$ superlattice has a third order susceptibility due to conduction band nonparabolicity which is about one hundred times that of bulk GaAs. The third order susceptibility due to conduction band nonparabolicity in the $Hg_{1-x}Cd_xTe/Hg_{1-y}Cd_yTe$ superlattice is approximately the same as in the bulk $Hg_{1-x}Cd_xTe$ alloy. The third order susceptibility in both superlattices due to the photoexcited plasma mechanism is substantially the same as in the corresponding bulk alloys. Including work done under the previous contract which was published during the present, there was a total of two chapters, fourteen written papers and fourteen spoken papers describing this work. One patent was issued and one application submitted.

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1.0 RESEARCH OBJECTIVES

The objectives of the contract are listed below:

(1) Determine the dependence of the power reflection coefficient upon signal and pump intensities for optical phase conjugation by resonant four-wave mixing in mercury cadmum telluride crystals.

(2) Study optical phase conjugation by four-wave mixing in epitaxial layers of mercury cadmium telluride.

(3) Investigate noncollinear phase matched far infrared radiation in mercury cadmium telluride.

(4) Measure the spectral dependence of the optical absorption coefficient in mercury cadmium telluride from 10 to 50 micrometers and separate band edge absorption with possible exciton effects from intervalance band and free carrier absorption.

(5) Measure the spectral dependence of the quantum efficiency in small gap mercury cadmium telluride from 10 to 50 micrometers.

(6) Determine the relative contributions of the microscopic mechanisms, including conduction band nonparabolicity, photoexcited plasma, and saturable absorption, to optical phase conjugation in $Hg_{1-x}Cd_xTe$.

(7) Investigate the quality of the phase conjugate return in $Hg_{1-x}Cd_xTe$.

(8) Investigate optical bistability in $Hg_{1-x}Cd_xTe$ arising from third order nonlinearities.

(9) Investigate theoretically the response time of nonlinear optical interactions produced by the various microscopic mechanisms in semiconductors.

(10) Investigate theoretically the nonlinear optical interaction mechanisms in semiconductor superlattices.

2.0 STATUS OF RESEARCH EFFORT AND FUTURE PLANS

The work carried out during the final period of the contract, 9 January 1985 - 15 June 1985, is described in this section.

2.1 Nonlinear Optics Experimental Investigations

Semiannual Technical Reports 6-8 described an effect never previously reported in the literature in which a degenerate four-wave mixing signal was modulated using an "erase beam". The experimental configuration is shown in Figure 1. The arrangement utilizes degenerate four-wave mixing in which 10.6μm wavelength pump and probe beams come together at an angle Θ on a $Hg_{1-x}Cd_xTe$ sample to form interference fringes. This modulation of the intensity in turn creates a diffraction grating in the sample. The sample used was $Hg_{.77}Cd_{.23}Te$ cooled to 80°K. The bandgap of this material at 80°K is 0.141eV. The grating in turn diffracts the pump and probe, resulting in the signal. If either pump or probe is blocked, the signal disappears. A third beam, the erase beam, is employed to irradiate the back side of the sample. This results in the signal being quenched or erased. The effect of erasing the signal increases with increasing erase beam intensity until it saturates at some low value of signal, see Figure 2. The effect did not require the erase beam to be coherent with the pump and probe. Because the energy of the radiation (0.117eV) is less than the bandgap energy, two-photon absorption is responsible for the photoexcitation.

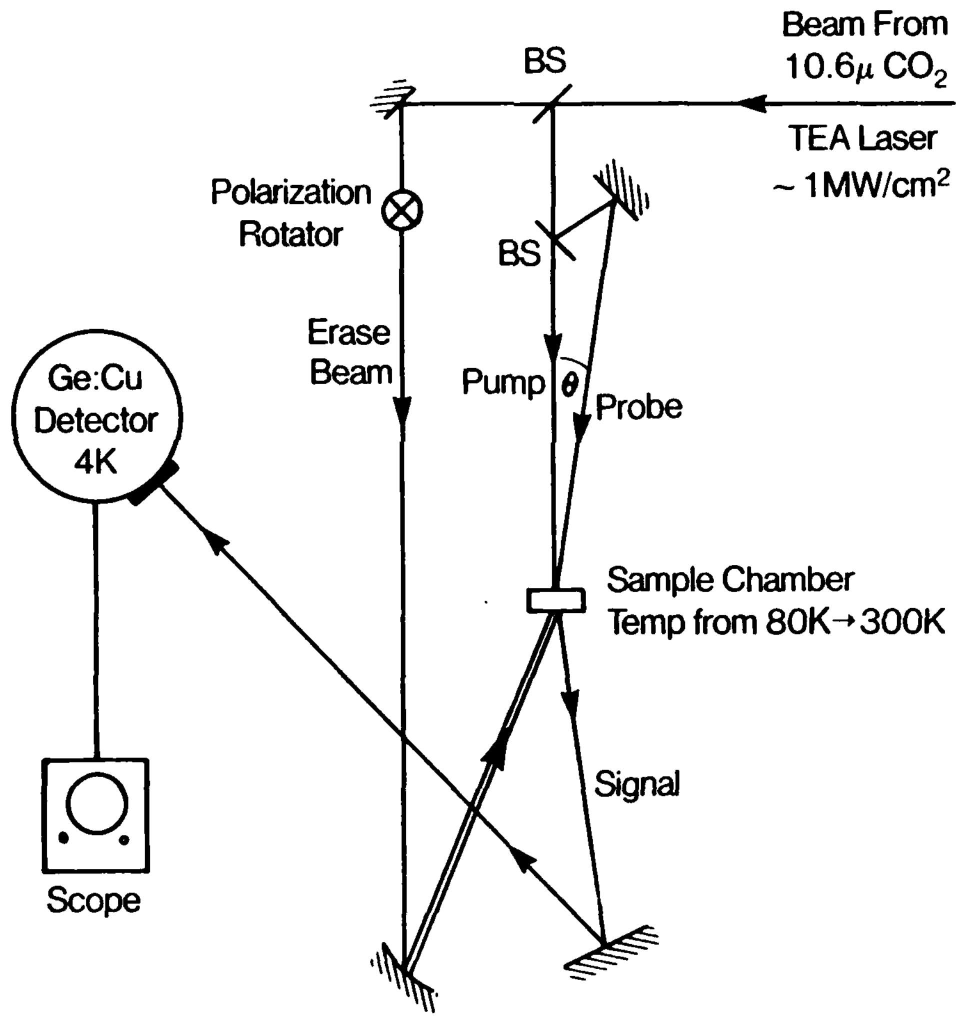

FIGURE 1

Experimental Arrangement

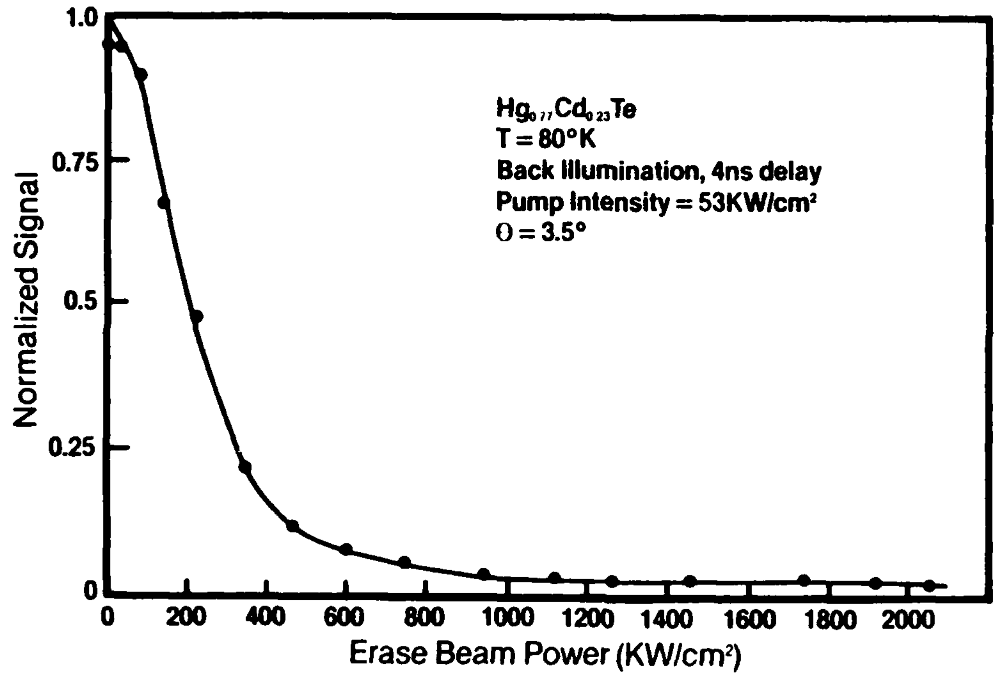

FIGURE 2

Effect of Erase Beam on Signal

During this reporting period, the effect of a time delay on the erase beam was examined. This was done by increasing the distance the erase beam had to travel before arriving at the sample. All of these experiments were done with a $Hg_{0.771}Cd_{0.229}Te$ sample at T=80°K and a pump/probe angular separation of $\Theta=3.5^{\circ}$ with pump intensities of about $50kW/cm^2$. The results are shown in Figure 3. It was found that the erase beam had the greatest effect ("erased" most of the signal) for the shortest time delay (4ns). As the delay was increased the effect was reduced. However, there was an effect even at a 65ns delay; (the pulse width of the CO_2 TEA laser is about 50ns). The erase beam experiment was also done with the polarization of the erase beam 90° to the incident beam. The erase beam was equally effective in quenching the phase conjugate signal in this configuration, which shows that erasure is not an interference effect.

The effect of delaying the pump and probe beams relative to the erase beam was also studied, see Figure 4. This arrangement also showed a decrease in signal; however, the signal _vs_ erase beam intensity had a smaller slope than did that with the erase beam delayed with respect to the pump and probe beams. There was little difference between the 7ns pump and probe delay and the 24ns pump and probe delay.

The effect of the erase beam on the phase conjugate signal as a function of angle for $\Theta=2.39^{\circ}$, 3.04° and 6.42° was also studied, see Figure 5. This experiment showed no significant angular dependence of the effect. The signal intensity _vs_ erase beam intensity for $\Theta=2.39^{\circ}$ was very similar to that at $\Theta=6.42^{\circ}$. The effect of the erase beam as a function of temperature and incident power was also studied, see Figures 6 and 7. No significant dependence on either parameter was seen.

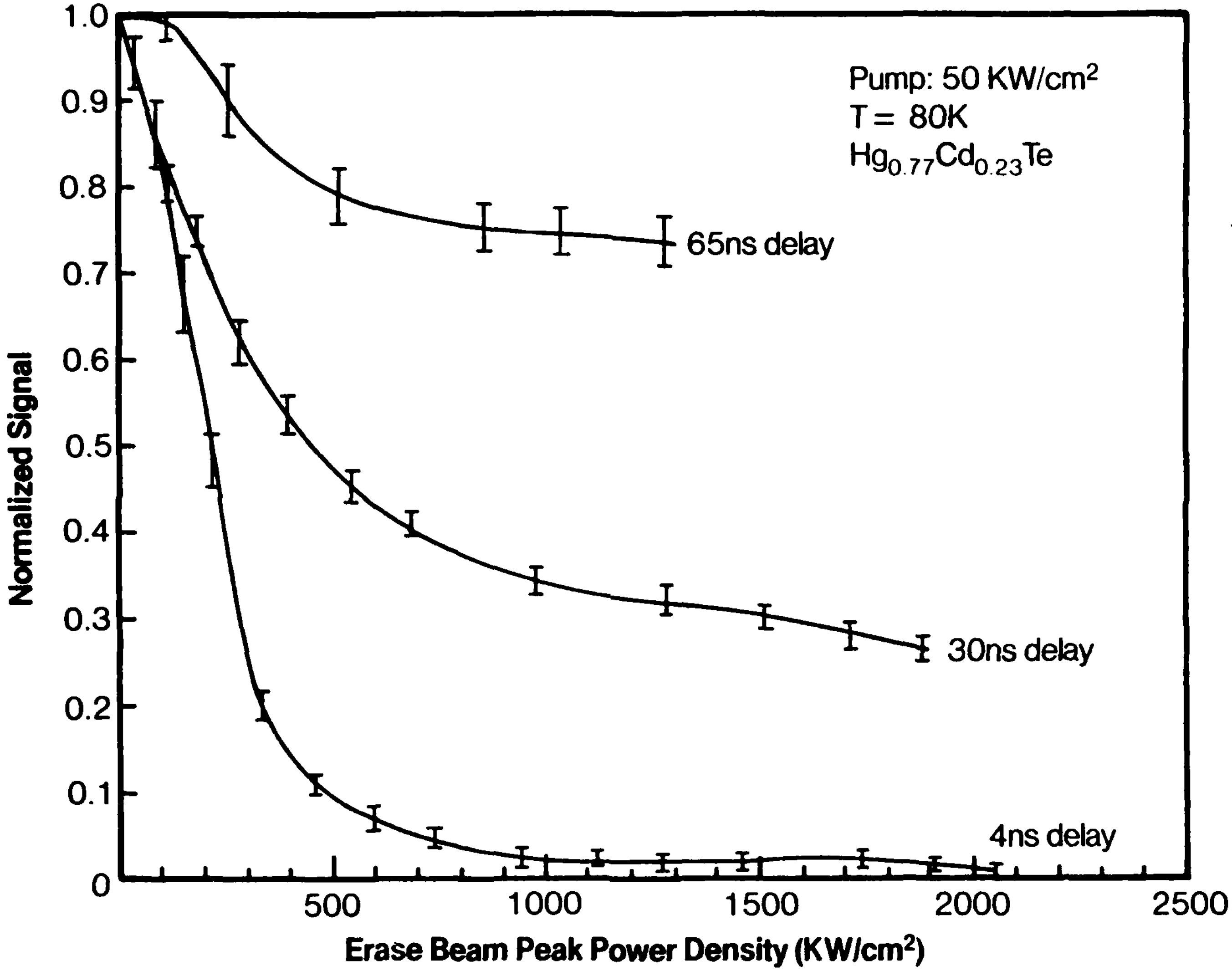

FIGURE 3

Effect of Erase Beam Time Delay

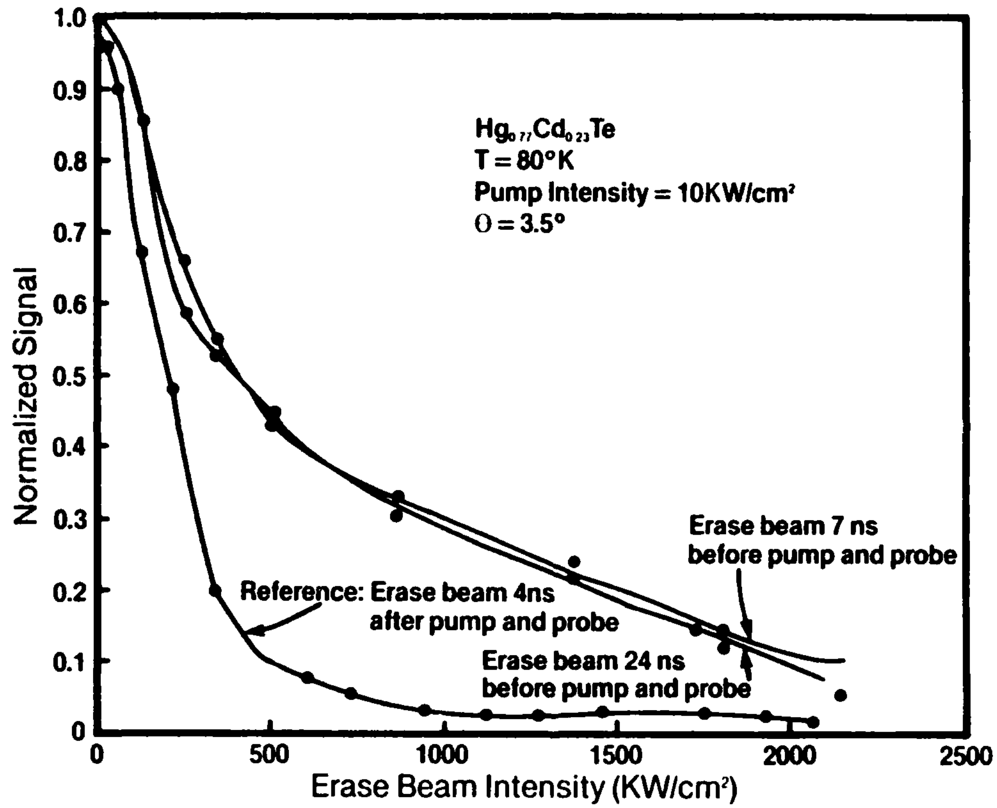

FIGURE 4

Effect of Erase Beam
Prior to Pump and Probe Beams

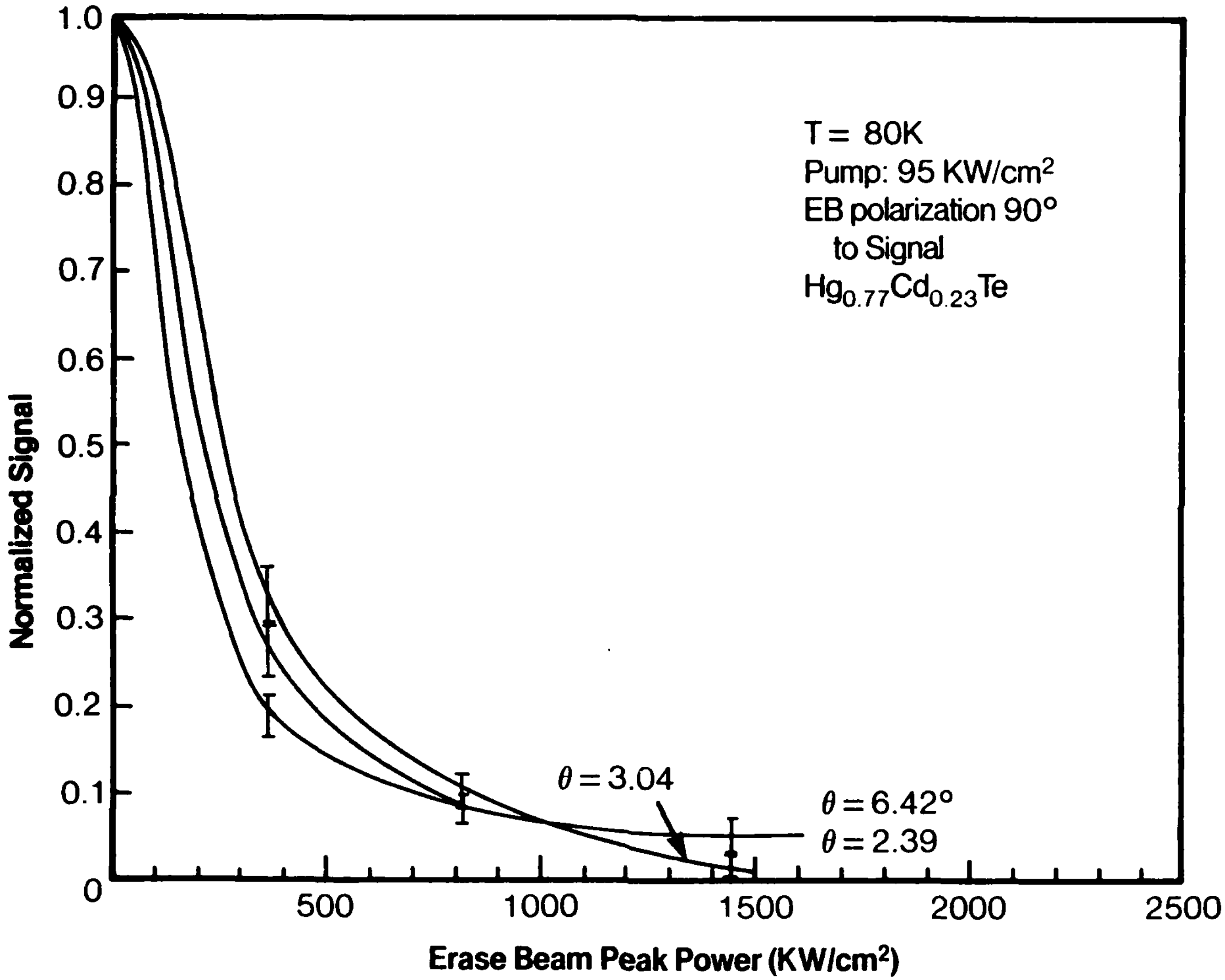

FIGURE 5

Angular Dependence of Erase Beam Effect

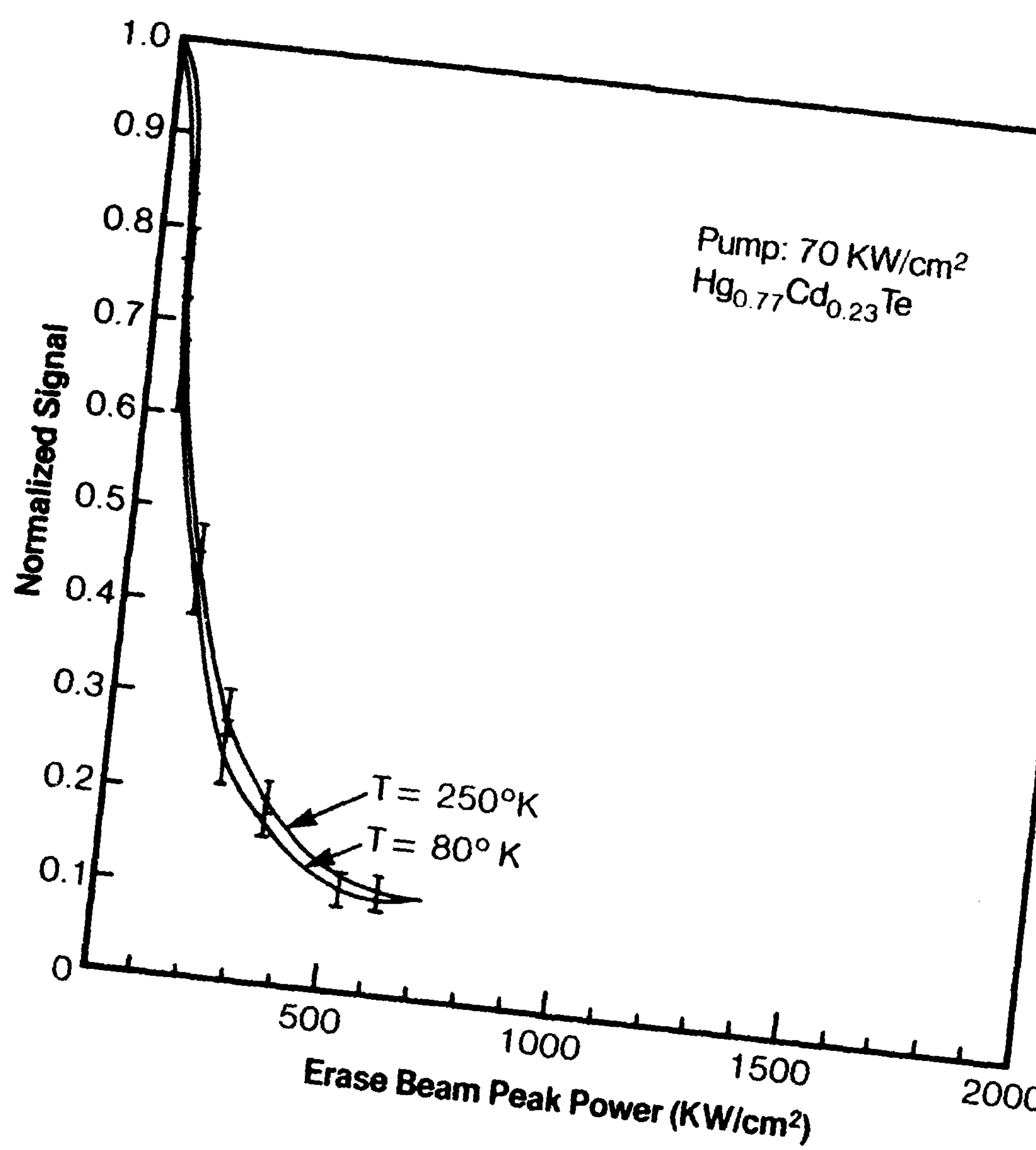

FIGURE 6

Temperature Dependence of Erase Beam Effect

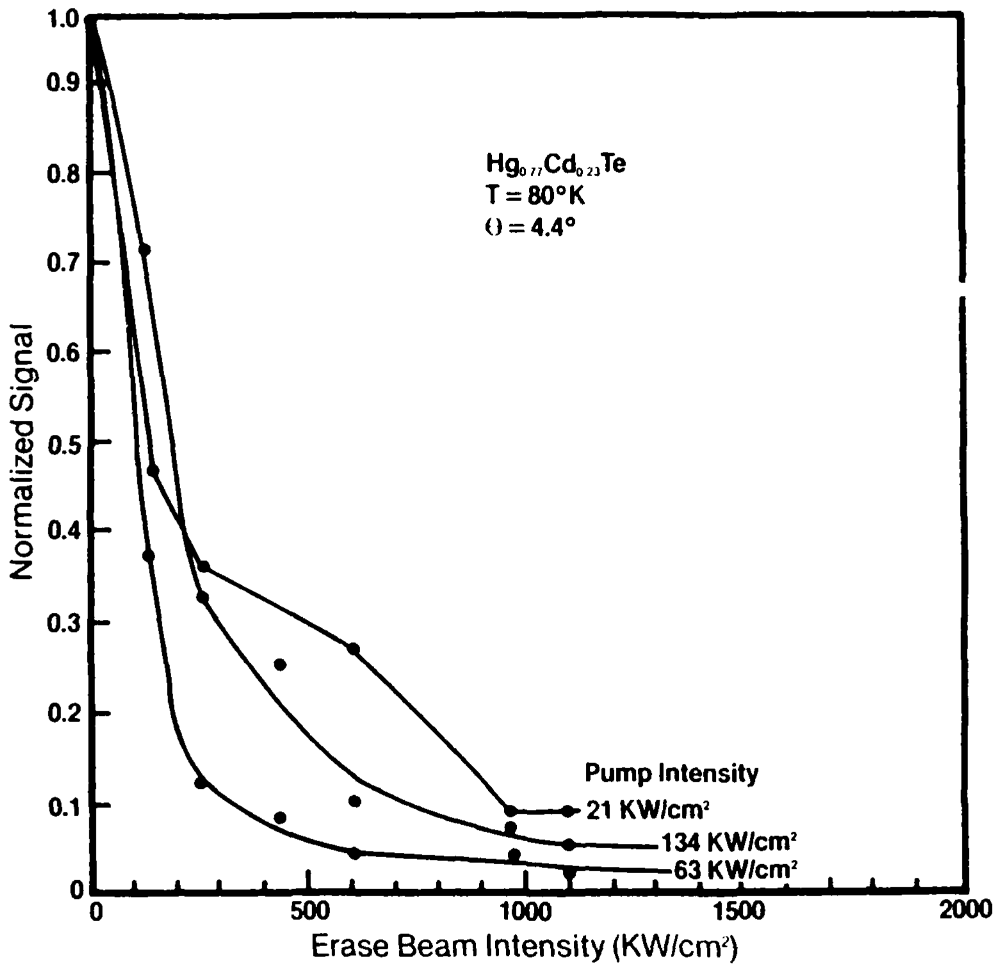

FIGURE 7

Pump Intensity Dependence of Erase Beam Effect

Frontal irradiation of the sample was also shown to give rise to the effect, see Figure 8. However, the effect was not as great as that seen with backside irradiation.

The physical mechanism underlying this erasure effect was described in Interim Technical Report 8. It is a result of the concentration dependent Auger lifetime of photoexcited carriers in $Hg_{1-x}Cd_xTe$. The phase conjugate signal arises from the probe beam being diffracted by the free carrier concentration grating generated by two-photon absorption and the interference of pump and probe beams. Those parts of the grating having high carrier concentrations are characterized by having an Auger lifetime τ_A which is inversely proportional to the square of the carrier concentration, i.e.,

$$\tau_A^g \propto \frac{1}{(n_o + \Delta n)^2}; \qquad (1)$$

where n_o and Δn are the equilibrium and photoexcited carrier concentrations respectively. The areas of the grating with no photoexcited carriers have

$$\tau_A \propto \frac{1}{{n_o}^2}. \qquad (2)$$

The "lifetime" of the diffraction grating then is approximately τ_A. If the erase beam is on, more carriers are photoexcited, not only at the concentration grating peaks but uniformly throughout the crystal. This uniform excitation results in the background carrier concentration being elevated above n_o, and τ_A is reduced further. If the erase beam is very intense, the differences in lifetimes between the grating's peaks and valleys become effectively zero. Because the power in the diffracted beam depends upon the square of $\chi^{(3)}$, the third order susceptibility, and $\chi^{(3)}$ is proportional to τ_A, the effect of the

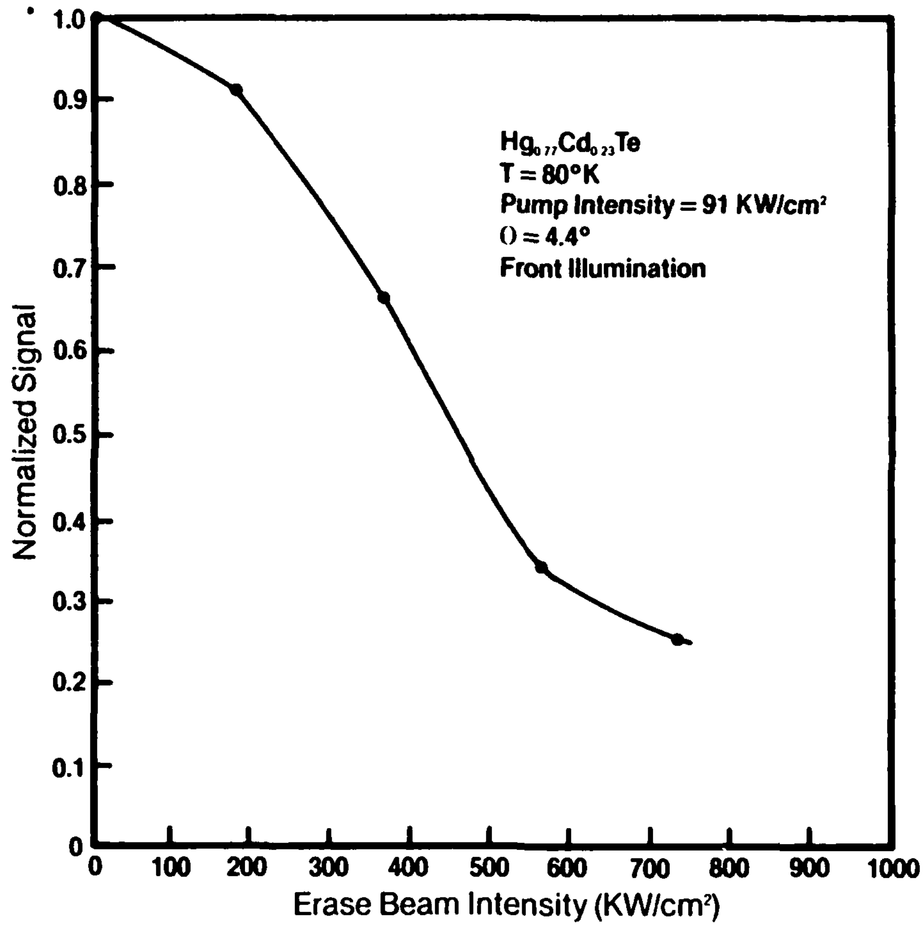

FIGURE 8

Erase Beam Effect with Frontal Irradiation

erase beam is to reduce the diffracted signal, almost eliminating it at high erase beam intensities. The effect of a time delay is to reduce the overlap between the pump/probe and erase pulses, thereby reducing the background photoexcited carrier concentration and the effect of the erase beam.

2.2 Nonlinear Optics Theoretical Investigations

As stated in Semiannual Technical Report 8, Honeywell entered into an agreement with Prof. Yia-Chung Chang of the Department of Physics, University of Illinois at Champaign-Urbana, to address research objectives (9) and (10). The results of his analysis leading to research objective number (10) were discussed in Semiannual Technical Report 8. During the period 9 January 1985 - 15 June 1985, Prof. Chang addressed objective (9), "Investigate theoretically the response time of nonlinear interactions produced by the various microscopic mechanisms in semiconductors." His analysis is contained in the manuscript "Transient Response of Nonlinear Optical Properties in Semiconductor Superlattices" which he has submitted for publication in the Journal of Applied Physics. His findings are summarized below.

The transient behaviors of optical bistability (OB) and degenerate four-wave mixing (DFWM) for a semiconductor superlattice (3-D case) or a quantum well (2-D case) were studied. It was determined that the up-switching time (t_u) for dispersive OB or DFWM due to band-nonparabolicity is of the same order of magnitude as the round-trip transit time (2L/v) within the semiconductor cavity. For absorptive OB or DFWM due to a photoexcited plasma, t_u is of the order of T_1, the interband recombination time. The down-switching

time (t_d), which is defined as the time required for the output signal to decay to a certain value, is found to be of the same order of magnitude as the cavity decay time (for OB) or the roundtrip transit time, irrespective of the mechanism. However, if the down-switching time (t_d) is defined as the time required for the system to return to the original state, then t_d should be of the order of the T_1 for absorptive OB or DFWM.

It was determined that in the direct saturation model, the semiconductor superlattice or quantum well medium does not yield the absorptive OB near the threshold optical frequency corresponding to the energy gap. In the Burstein-Moss model, only the semiconductor quantum well (or narrow-band semiconductor superlattice) can give rise to pronounced absorptive OB.

The *band-nonparabolicity mechanism* in semiconductor quantum wells was found to be quite promising for applications involving dispersive OB because of its fast switching time (~2L/v) and low switching power (10-100 kW/cm^2).

The transient behavior of DFWM in semiconductor superlattices is found to be similar to that in bulk semiconductors, although the semiconductor superlattice in the narrow-band limit (2-D case) tends to give a stronger saturation.

3.0 SUMMARY OF SIGNIFICANT ACCOMPLISHMENTS

Listed below are the significant accomplishments achieved during the period 9 January 1981 - 15 June 1985, organized according to research objectives:

(1) Objective: Determine the dependence of the power reflection coefficient upon signal and pump intensities for optical phase conjugation by resonant four-wave mixing in mercury cadmium telluride crystals.

Accomplishment: Optical phase conjugation by bandgap resonant four-wave mixing in $Hg_{1-x}Cd_xTe$ was studied at 77^oK. The power reflection coefficient was experimentally determined as a function of CO_2 laser pump and probe intensities. From these data, values of $\chi^{(3)}$ of $3x10^{-2}$esu were measured. Close agreement was found with theory[1]. These experiments were described in the following publication:

- M.A. Khan, R.L.H. Bennett, and P.W. Kruse, "Bandgap Resonant Optical Phase Conjugation in N-Type $Hg_{1-x}Cd_xTe$ at 10.6 μm," Optics Lett. 6, 650(1981).

(2) Objective: Study optical phase conjugation by four-wave mixing in epitaxial layers of mercury cadmium telluride.

Accomplishment: A computer-controlled (hp-9825) laser scanner and data acquisition system was assembled to obtain phase conjugation data from (Hg,Cd)Te epitaxial layers. One sample was evaluated. It consisted of a CdTe substrate on which was grown a 20 μm thick epitaxial layer of n-type $Hg_{0.79}Cd_{0.21}Te$ having a free electron concentration of $1x10^{15}cm^{-3}$. Over this was grown a 10 μm thick epitaxial layer of n-type $Hg_{0.65}Cd_{0.35}Te$. A weak phase conjugate signal (S/N = 5) was detected at 77^oK in response to 10.6 μm radiation from a CO_2 laser. The limitation in signal was due to the layer being too thin to absorb radiation efficiently. This was the first report of optical phase conjugation from epitaxial layers of $Hg_{1-x}Cd_xTe$,

1. R.K. Jain and D.G. Steel, Appl. Phys. Lett. 37, 1(1980).

and possibly from epitaxial layers of any material. This work was reported in two publications:

- M.A. Khan and P.W. Kruse, "A Computer Controlled laser Scanning System for Characterizing $Hg_{1-x}Cd_xTe$ Crystals", Conference on Lasers and Electro Optics (CLEO), Phoenix, 14-16 April 1982.

- M.A. Khan, P.W. Kruse, R.A. Wood, and Y.K. Park, "Optical Phase Conjugation and Nonlinear Fabry-Perot Effects in Epitaxial Layers of $Hg_{1-x}Cd_xTe$", Conference on Lasers and Electro-Optics (CLEO), Baltimore, 19 May 1983.

(3) <u>Objective</u>: Investigate noncollinear phase matched far infrared radiation in mercury cadmium telluride.

<u>Accomplishment</u>: Experiments of this type were initiated under the previous contract in collaboration with investigators at MIT. They met with only slight success; the generation of far infrared radiation is a very inefficient process. After consultation with AFOSR, it was decided that it would be more productive to work on the other research tasks.

(4) <u>Objective</u>: Measure the spectral dependence of the optical absorption coefficient in mercury cadmium telluride from 10 to 50 micrometers and separate band edge absorption with possible exciton effects from intervalence band and free carrier absorption.

<u>Accomplishment</u>: Optical absorption measurements from 10 μm to 40 μm were carried out on eight bulk $Hg_{1-x}Cd_xTe$ samples (3 p-type and 5 n-type) with compositions (x-values) ranging from 0.19 to 0.40. Data were also taken on epitaxial layers of $Hg_{1-x}Cd_xTe$. A computer program was developed which permitted calculation of the contribution to the optical absorption cross-

section from all the major absorption mechanisms including interband, intraband, lattice, and impurity absorption. The data for both bulk and epitaxial samples were compared with theory. The results were presented in the spoken paper:

- "An Investigation of the Far Infrared Optical Properties of $Hg_{1-x}Cd_xTe$" by T. N. Casselman and G. Hansen, 1983 Mercury Cadmium Telluride Workshop, Dallas, 8-10 February 1983.

The results were also published in the following written publication:

- T.N. Casselman and G.L. Hansen, "An Investigation of the Far Infrared Optical Properties of $Hg_{1-x}Cd_xTe$", J. Vac. Sci. Tech. A1(3), 1683(1983).

(5) Objective: Measure the spectral dependence of the quantum efficiency in small gap mercury cadmium telluride from 10 to 50 micrometers.

Accomplishment: Due to the departure of T. N. Casselman, this work was redirected. However, preliminary results were reported in two publications:

- G.L. Hansen, J.L. Schmit, and T.N. Casselman, "Energy Gap vs Composition and Temperature in HgCdTe", J. Appl. Phys. 53, 7099(1982).

- G.L. Hansen and J.L. Schmit, "Calculation of Intrinsic Carrier Concentration in $Hg_{1-x}Cd_xTe$", J. Appl. Phys. 54, 1639(1983).

(6) Objective: Determine the relative contributions of the microscopic mechanisms, including conduction band

nonparabolicity, photoexcited plasma, and saturable absorption, to optical phase conjugation in $Hg_{1-x}Cd_xTe$.

Accomplishment: To determine the relative contributions of the microscopic mechanisms, a series of optical phase conjugation experiments was carried out on four n-type samples of $Hg_{1-x}Cd_xTe$ at 295°K, 77°K, and 12°K. The sample x-values were 0.232, 0.231, 0.225, and 0.216. The pump and probe beams were provided by four CO_2 lasers, the choice depending upon the experiment. For studying nonresonant behavior a pulsed CO_2 TEA laser was employed. For studying bandgap resonant behavior a CW CO_2 laser was employed. For studying spin resonant behavior, two Q-switched CO_2 lasers were employed. Both forward mode and reflective mode signals were obtained. The microscopic mechanisms were identified. Values of $\chi^{(3)}$ were determined and compared with theory. In general $\chi^{(3)}$ was of the order of $1\text{x}10^{-8}$esu for conduction band nonparabolicity, $1\text{x}10^{-4}$esu for spin resonance, and $3\text{x}10^{-2}$esu for photoexcited plasma. These experiments were described in the following spoken papers:

- Paul W. Kruse, Muhammad A. Khan, and John F. Ready, "Reflective and Forward Mode Optical Phase Conjugation in $Hg_{1-x}Cd_xTe$," International Conference on Excited States and Multiresonant Nonlinear Optical Processes in Solids, Aussois, France, 18-20 March, 1981.

- Muhammad A. Khan, Paul W. Kruse, and R.L.H. Bennet, "Optical Phase Conjugation in $Hg_{1-x}Cd_xTe$ in the Forward and Reflective Modes", Conference on Lasers and Electro-Optics (CLEO), Washington, D. C., 10-12 June 1981.

- P.W. Kruse, M.A. Khan, and J.F. Ready, "Optical Phase Conjugation in (Hg,Cd)Te", SPIE 25th Annual International Technical Symposium and Exhibit, San Diego, 24-28 August 1981.

- P.W. Kruse and M.A. Khan, "Nonresonant and Bandgap Resonant Optical Phase Conjugation in $Hg_{0.784}Cd_{0.216}Te$", Conference on Lasers and Electro-Optics (CLEO), Phoenix, 14-16 April 1982.

- Paul W. Kruse and M. Asif Khan, "Mechanisms of Optical Phase Conjugation in (Hg,Cd)Te", International Conference on Lasers '82, New Orleans, 13-17 December 1982.

These experiments also were described in the following written publications:

- P.W. Kruse, M.A. Khan, and J.F. Ready, "Optical Phase Conjugation in (Hg,Cd)Te", Proceedings of the Symposium on Wavefront Distortions in Power Optics, SPIE, Bellingham, Washington, (1981).

- P.W. Kruse and M.A. Khan, "Mechanisms of Optical Phase Conjugation in $Hg_{1-x}Cd_xTe$", Proc. Int'l. Conf. on Lasers '82, R.C. Powell, ed., STS Press, McLean, Va. (1983).

(7) Objective: Investigate the quality of the phase conjugate return in $Hg_{1-x}Cd_xTe$.

Accomplishment: A new effect was discovered, in which the phase conjugate signal could be quenched or erased by a CO_2 laser beam incident upon the same region of the sample in which the pump and probe beams were incident. The mechanism was found to include Auger recombination whose rate is enhanced by photo-excited carriers obtained

by two-photon absorption, see Section 2 of this report. An invention disclosure has been submitted to Honeywell's legal department as a candidate for filing with the U.S. Patent Office:

- M.A. Khan and J. Lehman, "Device for Modulating 10.6μm Radiation".

These experiments were described in two spoken presentations:

- M. Asif Khan, J. Lehman, and P.W. Kruse, "Dynamics of Real-time Electron Gratings in $Hg_{1-x}Cd_xTe$", International Conference on Lasers '84, San Francisco, 26-30 November 1984.

- David K. Arch, M. Asif Khan, John Lehman, and Paul W. Kruse, "Erasure of Phase Conjugate Signals in $Hg_{0.77}Cd_{0.23}Te$", 1985 Annual Meeting of the Optical Society of America, Washington, D.C., 14-18 October 1985.

(8) Objective: Investigate optical bistability in $Hg_{1-x}Cd_xTe$ arising from third order nonlinearities.

Accomplishment: Optical bistability experiments were carried out on two Fabry-Perot $Hg_{1-x}Cd_xTe$ cavities ($x = 0.217$ and 0.227) at $77^{o}K$. Some indications of bistable operation were observed; the transmitted intensity vs incident intensity exhibited discontinuities, but no hysteresis loops were seen. Due to inhomogeneities in composition or nonuniform thickness, the transmitted intensity varied with position on the faces of the samples. A novel method of measuring the value of the nonlinear contribution to the refractive index (n_2) was developed based upon a Mach-Zender interferometer. Measurements of n_2 were compared to

values calculated from the third order susceptibility $\chi^{(3)}$ and excellent agreement was found. This work was reported in the spoken paper:

- M.A. Khan, P.W. Kruse, R.A. Wood and Y.K. Park, "Optical Phase Conjugation and Nonlinear Fabry-Perot Effects in Epitaxial Layers of $Hg_{1-x}Cd_xTe$," Conference on Lasers and Electro-Optics (CLEO), Baltimore, 19 May 1983.

(9) Objective: Investigate theoretically the response time of nonlinear optical interactions produced by the various microscopic mechanisms in semiconductors.

Accomplishments: The temporal behavior of degenerate four-wave mixing and optical bistability was studied for a superlattice or quantum well. Upswitching and downswitching times were analyzed for both absorptive (photoexcited plasma) and dispersive (band nonparabolicity) mechanisms. This work is described in a paper which has been submitted for publication:

- Y-C Chang, "Transient Response of Nonlinear Optical Properties in Semiconductor Super-lattices", submitted to Journal of Applied Physics.

(10) Objective: Investigate theoretically the nonlinear optical interaction mechanisms in semiconductor superlattices.

Accomplishments: The third order susceptibility $\chi^{(3)}$ due to both the conduction band nonparabolicity and the photoexcited plasma mechanisms in both $GaAs/Al_xGa_{1-x}As$ and $Hg_{1-x}Cd_xTe/Hg_{1-y}Cd_yTe$ superlattices was analyzed theoretically. The analysis showed that the optimized $GaAs/Al_xGa_{1-x}As$ superlattice has a value of $\chi^{(3)}$ due to conduction band nonparabolicity about two orders of

magnitude larger than that of bulk GaAs. For a small bandgap $Hg_{1-x}Cd_xTe/Hg_{1-y}Cd_yTe$ superlattice, $\chi^{(3)}$ due to conduction band nonparabolicity is approximately the same as that of bulk $Hg_{1-x}Cd_xTe$. It was also determined that the value of $\chi^{(3)}$ in a $GaAs/Al_xGa_{1-x}As$ superlattice arising from the photoexcited plasma mechanism is substantially the same as that of the $Al_xGa_{1-x}As$ alloy. The value of $\chi^{(3)}$ in a $Hg_{1-x}Cd_xTe/Hg_{1-y}Cd_yTe$ superlattice due to the photoexcited plasma mechanism can be at most three times greater than in the $Hg_{1-x}Cd_xTe$ alloy. These results were published in the paper:

- Y.C. Chang, "Non-Linear Optical Properties of Semiconductor Superlattices", J. Appl. Phys. 58, 499(1985).

4.0 WRITTEN PUBLICATIONS IN TECHNICAL JOURNALS

The following publications representing work done under the prior Contract F49620-77-C-0028 (1 January 1977 - 31 December 1980) were published during the period of the present contract F49620-81-C-0034 (9 January 1981 - 15 June 1985).

Chapters

- .W. Kruse and J.F. Ready, "Nonlinear Optical Effects in $Hg_{1-x}Cd_xTe$", Semiconductors and Semimetals 16, R.K. Willa[illegible]son and A.C. Beer, eds., Academic Press, New York 1981).

- P.E. Petersen,"Auger Recombination in (Hg,Cd)Te", Semiconductors and Semimetals 18, R.K. Willardson and A.C. Beer, eds., Academic Press, New York (1981).

Scientific Papers

- T.N. Casselman and P.E. Petersen, "Calculation of the Carrier Concentration Dependence of the Auger Lifetime in Degenerate N-type (Hg,Cd)Te," Solid State Comm. 39,1117(1981).

- T.N. Casselman, "Calculation of the Auger Lifetime in P-Type $Hg_{1-x}Cd_xTe$", J. Appl. Phys. 52, 848 (1981).

- T.J. Moravec and T.W. Orent, "Electron Spectroscopy of Ion Beam and Hydrocarbon Plasma Generated Diamondlike Carbon Films," J. Vac. Sci. Technol. 18, 226 (1981).

- H. Vora and T.J. Moravec, "Structural Investigations of Thin Films of Diamondlike Carbon", J. Appl. Phys. 52, 6151 (1981).

- T.N. Casselman, "Calculations of the Auger Lifetime in Degenerate N-type (Hg,Cd)Te", Physics of Narrow Gap Semiconductors: Proceedings of the 4th International Conference on the Physics and Chemistry of (Hg,Cd)Te, Linz, Austria, September 1981, Springer-Verlag, Berlin (1982).

The following publications representing work carried out under both contracts F49620-77-C-0028 and F49620-81-C-0034 were published during the period of the present contract.

- P.W. Kruse, M.A. Khan, and J.F. Ready, "Optical Phase Conjugation in (Hg,Cd)Te", Proceedings of the Symposium on Wavefront Distortions in Power Optics, SPIE, Bellingham, Washington, (1981).

- P.W. Kruse and M.A. Khan, "Mechanisms of Optical Phase Conjugation in $Hg_{1-x}Cd_xTe$", Proceedings of the International Conference on Lasers '82, R.C. Powell, ed., STS Press, McLean, Va. (1983).

The following publications representing work done under contract F49620-81-C-0034 were published during this period.

- M.A. Khan, R.L.H. Bennett, and P.W. Kruse, "Bandgap Resonant Optical Phase Conjugation in N-Type $Hg_{1-x}Cd_xTe$ at 10.6 μm", Optics Lett. 6, 650 (1981).

- T.N. Casselman and G.L. Hansen, "An Investigation of the Far Infrared Optical Properties of $Hg_{1-x}Cd_xTe$", J. Vac. Sci. Tech. A1(3), 1683(1983).

- G.L. Hansen, J.L. Schmit, and T.N. Casselman, "Energy Gap vs. Composition and Temperature in $Hg_{1-x}Cd_xTe$", J. Appl. Phys. 53, 7099 (1982).

- G.L. Hansen and J.L. Schmit, "Calculation of Intrinsic Carrier Concentration in $Hg_{1-x}Cd_xTe$," J. Appl. Phys. 54, 1639 (1983).

- Y-C Chang, "Nonlinear Optical Properties of Semiconductor Superlattices," J. Appl. Phys. 58, 499(1985).

The following publication representing work done under Contract F49620-81-C-0034 has been submitted for publication.

- Y-C Chang, "Transient Response of Nonlinear Optical Properties in Semiconductor Superlattices," submitted to Journal of Applied Physics.

5.0 PROFESSIONAL PERSONNEL ASSOCIATED WITH RESEARCH EFFORT

The following personnel with B.S. or higher degrees participated in the research effort during the period of the contract.

Dr. Paul W. Kruse, Chief Research Fellow
Dr. Muhammad Asif Khan, Senior Principal Research Scientist

Dr. David K. Arch, Principal Research Scientist
Dr. Darryl L. Smith, Senior Principal Research Scientist
Dr. R. Andrew Wood, Senior Principal Research Scientist
Mr. Thomas N. Casselman, Senior Principal Research Scientist
Mr. Joseph L. Schmit, Senior Principal Research Scientist
Mr. Paul R. Haugen, Principal Research Scientist
Mr. S. M. LaCroix, Graduate Assistant
Mr. John A. Lehman, Student Aide
Mr. Gary Hansen, Student Aide
Prof. Y-C Chang, Assistant Professor, University of Illinois

6.0 INTERACTIONS

6.1 Spoken Papers Presented at Scientific Meetings

The following spoken papers representing work done under the prior contract F49620-77-C-0028 (1 January 1977 - 31 December 1980) were presented during the period of the present contract F49620-81-C-0034 (9 January 1981 - 15 June 1985).

- Paul W. Kruse, "Optical Phase Conjugation by Four-Wave Mixing in Mercury Cadmium Telluride," Huntsville, Alabama Electro-Optical Section and Working Group, OSA and SPIE, 6 January 1981 (by invitation).

- T.N. Casselman, "Electron-Hole Pair Recombination Mechanisms that Limit the Performance of Infrared Photodetectors", Physics Department Colloquium, University of Illinois, Chicago, 20 May 1981.

- T.N. Casselman, "Calculations of the Auger Lifetime in Degenerate n-type (Hg, Cd)Te", 4th International Conference on the Physics of Narrow Band Semiconductors, Linz, Austria, September, 1981.

- T.N. Casselman, "On the Problem of Determining the Lifetime Limiting Mechanisms in (Hg,Cd)Te from Lifetime Measurements", U. S. Workshop on the Physics and Chemistry of (Hg,Cd)Te, Minneapolis, 26-30 October 1981.

The following spoken papers representing work done under both the prior contract F49620-77-C-0028 (1 January 1977 - 31 December 1980) and the present contract F49620-81-C-0034(9 January 1981 - 15 June 1985) were presented during the period of the present contract.

- Paul W. Kruse, Muhammad A. Khan, and John F. Ready, "Reflective and Forward Mode Optical Phase Conjugation in $Hg_{1-x}Cd_xTe$," International Conference on Excited States and Multiresonant Nonlinear Optical Processes in Solids, Aussois, France, 18-20 March, 1981.

- Muhammad A. Khan, Paul W. Kruse, and R.L.H. Bennet, "Optical Phase Conjugation in $Hg_{1-x}Cd_xTe$ in the Forward and Reflective Modes", Conference on Lasers and Electro-Optics (CLEO), Washington, D. C., 10-12 June 1981.

- P.W. Kruse, M.A. Khan, and J.F. Ready, "Optical Phase Conjugation in (Hg,Cd)Te", SPIE 25th Annual International Technical Symposium and Exhibit, San Diego, 24-28 August 1981.

The following spoken papers representing work done under the present Contract F49620-81-C-0034 (9 January 1981- 15 June 1985) were presented during the period of the present contract.

- M.A. Khan and P.W. Kruse, "A Computer Controlled Laser Scanning System for Characterizing $Hg_{1-x}Cd_xTe$ Crystals", Conference on Lasers and Electro-Optics (CLEO), Phoenix, 14-16 April 1982.

- P.W. Kruse and M.A.Khan, "Nonresonant and Bandgap Resonant Optical Phase Conjugation in $Hg_{0.784}Cd_{0.216}Te$", Conference on Lasers and Electro-Optics (CLEO), Phoenix, 14-16 April 1982.

- Paul W. Kruse and M. Asif Khan, "Mechanisms of Optical Phase Conjugation in (Hg,Cd)Te", International Conference on Lasers '82, New Orleans, 13-17 December 1982.

- M.A. Khan, P.W. Kruse, R.A. Wood, and Y.K. Park, "Optical Phase Conjugation and Nonlinear Fabry-Perot Effects in Epitaxial Layers of $Hg_{1-x}Cd_xTe$", Conference on Lasers and Electro-Optics (CLEO), Baltimore, 19 May 1983.

- M. Asif Khan, J. Lehman, and P.W. Kruse, "Dynamics of Real-Time Electron Gratings in $Hg_{1-x}Cd_xTe$", International Conference on Lasers '84, San Francisco, 26-30 November 1984.

- T.N. Casselman and G. Hansen, "An Investigation of the Far Infrared Optical Properties of $Hg_{1-x}Cd_xTe$," 1983 Mercury Cadmium Telluride Workshop, Dallas, 8-10 February 1983.

The following spoken paper representing work done under the present Contract F49620-81-C-0034 (9 January 1981 - 15 June 1985) will be presented at a later date.

- David K. Arch, M. Asif Khan, John Lehman, and Paul W. Kruse, "Erasure of Phase Conjugate Signals in $Hg_{0.77}Cd_{0.23}Te$", 1985 Annual Meeting of the Optical Society of America, Washington, D.C., 14-18 October 1985.

6.2 Consultative and Advisory Functions

- Paul W. Kruse presented a seminar on optical phase conjugation at AFOSR on 21 June 1982.

6.3 Other Interactions

- During the first half of 1981, T.N. Casselman discussed models for free electron absorption with Prof. B. Jensen of Boston University.

- T.N. Casselman was the cochairman of the U.S. Workshop on the Physics and Chemistry of (Hg,Cd)Te,held in Minneapolis October 26-30, 1981. P.W. Kruse and M.A. Khan attended. Numerous conversations were held with the participants regarding far infrared photoeffects and optical phase conjugation in (Hg,Cd)Te.

- T.N. Casselman discussed the warping of the heavy hole band and the measurement of the warping factors in (Hg,Cd)Te with Prof. M. Weiler of M.I.T. during the last half of 1981.

- Dr. Brian S. Wherrett, Center for Applied Quantum Electronics, North Texas State University, on leave from Heriot-Watt University, Edinburgh, Scotland visited Honeywell's Corporate Technology Center on 6 August 1982. He presented a talk "Resonant Nonlinear Optical Processes in Semiconductors" to Honeywell scientists. The rest of the day was spent discussing his research and Honeywell's research in nonlinear optical effects.

- During the first half of 1983, Darryl Smith was on sabbatical at the California Institute of Technology. While there he worked closely with Professor T. C. McGill and his research group. Some of the work on the formal development of superlattice electronic structure theory

was done in collaboration with Mr. Christian Mailhiot, a graduate student in Professor McGill's group.

- Two samples of $Hg_{1-x}Cd_xTe$ were provided to Prof. Jacek Furdyna, Purdue University, on 23 July 1985 to be used in to his investigations of dilute magnetic semiconductors.

7.0 NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

The following patent representing work done under the prior contract F49620-77-C-0028 (1 January 1977-31 December 1980) was issued during the period of the present contract F49620-81-C-0034 (9 January 1981 - 15 June 1985).

- U.S. Patent No. 4,316,147, "Apparatus for Determining the Composition of Mercury-Cadmium Telluride and Other Alloy Semiconductors", P.W. Kruse, M.A. Khan, and J.F. Ready.

The following disclosure representing work done under the present contract F49620-81-C-0034 (8 January 1981 - 15 June 1985) has been submitted to Honeywell's legal department as a candidate for filing with the U.S. Patent Office.

- M.A. Khan and J. Lehman, "Device for Modulating 10.6μm Radiation".

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